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Abstract

A geologic map of the Nez Perce drainage basin in southwestern Montana offers an understanding of the developing paleotopography of the area following the Laramide orogeny, ca. 65 ma. In this project, a small drainage basin was studied in detail, focusing on the geomorphology, structure, lithology, and ages of the various rock units. Based on the results of these studies and the relationships found among four major gravel units mapped within the basin, the basin development was approximated. The youngest unit is a fine-grained (mean diameter = 8.23 cm) channel deposit within Nez Perce Creek, sourced from within the basin, based upon gneiss and quartzite derived from the present drainage. The next-youngest unit is a fine-grained (mean diameter = 10.92 cm) alluvial sheet deposit forming broad flat surfaces adjacent to Nez Perce Creek in the central basin, which was also sourced from within the present drainage based upon gneiss and quartzite derived from the present drainage. The next unit, a coarse-grained (mean diameter = 22.90 cm) Miocene gravel creating the western divide of the basin, was sourced from the Highland Mountains to the north. The oldest unit, a coarse-grained (mean diameter = 39.88 cm) debris flow, is interlayered with Eocene basalt and rhyolite tuff, allowing its age to be bracketed to ca. 48 ma using Ar39/Ar40. Based on unique lithology, this unit was sourced from the Pioneer Mountains to the east. One large fault separates Archean gneiss bedrock on the east side of the basin from younger gravel deposits on the west. Several younger normal faults within the divide gravel indicate tectonic activity more recent than the Miocene time. This evidence of recent faulting, along with a lack of evidence of geomorphology shaped by fluvial erosion, indicates that basin development was more recent than previously assumed (Reynolds, 1979; Rupple, 1993) and was controlled more by structural than by fluvial forces.

Introducion

The Basin and Range region covers much of the western United States and southwestern Canada. It is characterized by alternating north-south trending mountain ranges separated by broad basins, locally called “holes” (Fig. 1). The northern portion of the Basin and Range includes an area in southwestern Montana that extends from a strike-slip structural discontinuity, the Lewis and Clark line, at the northern margin to the Snake River Plain and the Yellowstone Plateau at the southern margin (Reynolds, 1979; Wernicke et al., 1987). In southwestern Montana, the geology and geomorphology of these isolated mountain ranges result from several periods of tectonic activity which changed from compressive forces with resulting folding and thrust faulting that dominated during the Laramide orogeny (mountain building event) beginning in the late Cretaceous (ca. 65 ma) to dominantly extensional forces during the formation of the Basin and Range, beginning ca. 55-49 ma (Paleocene to middle Eocene). Extension continued across a wider belt than the initial deformation area after ca. 45 ma (middle Miocene) to the present time (Constenius, 1996).

Three major hypotheses have addressed details of the Basin and Range development within southwestern Montana following the initial compression and thrust faulting of the Laramide orogeny. The first hypothesis suggests that the basins and mountain ranges present in southwestern Montana today are products of normal dip-slip faulting resulting from crustal arching and crustal extension beginning in the Cenozoic (e.g., Scholten, 1968; Reynolds, 1979). The mountain blocks attained their general present-day outlines in the middle Miocene (15 ma), and uplift has continued to the present time. Fault scarps on the east sides of the basins are steeper than those along the western basin margins, and the basins are filled with 100-3000 m of Cenozoic sedimentary and volcanic detritus (Reynolds, 1979). The first hypothesis considers each mountain range as an isolated faulted block, not a structural whole (Rupple, 1993).

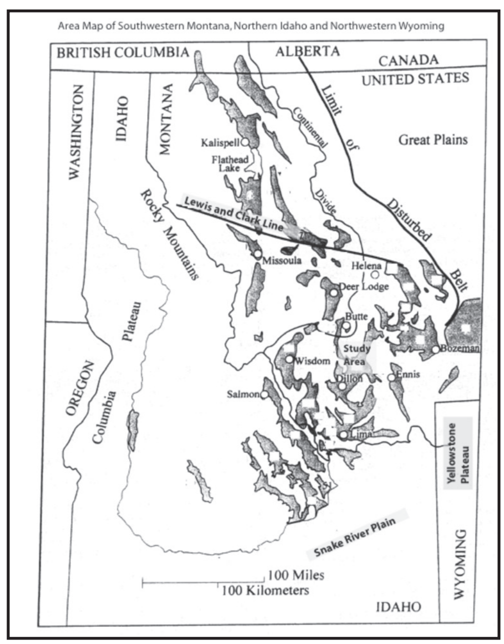

Figure. 1 Map of study area and surrounding features modified from Rasmussen (2003).

As a second hypothesis, Rupple (1993) suggested that extensional collapse began in the middle Eocene (40 ma) and that the deep basins and rhombohedral-shaped ranges present today had formed by the late early Miocene, ca. 15 ma, along preexisting north-northeast and northwest oriented faults. In contrast to previous workers, Rupple argued that more recent (Pliocene) fault movement has been primarily along the north-northeast faults that have primarily experienced strike-slip (lateral) or oblique-slip (lateral and vertical) movement rather than dip-slip movement. Causes of reactivation along the existing northwest-trending faults include both extensional collapse due to doming and lateral extrusion due to the volcanism that produced the Yellowstone Hot Spot (Rupple, 1993).

Presenting a third hypothesis of Cenozoic basin development in southwestern Montana, Fritz and Sears (1993) proposed that the modern basins and mountains formed only in the last 2 million years. After the Laramide orogeny and by the early Miocene (20 ma), extension formed broad basins which filled with igneous flows and volcaniclastic sediments. As stated in the previous hypotheses, this Fritz and Sears state that a broad valley that drained southeast existed between 16 and 6 ma and partially filled with more sediment. This broad valley was broken up by the activity of the Yellowstone Hot Spot so that some sections of the paleovalley were uplifted to form mountains and other sections were dropped to form the smaller present-day basins. Locally, this deformation caused flow reversal of some rivers and a northeastern shift in regional drainage. In contrast to Reynolds (1979), Wernicke et al. (1987), and Rupple (1993), Fritz and Sears argued that the modern mountains and basins of southwest Montana were ≤ 2 ma old. Unlike Rupple (1993), Fritz and Sears also argued that movement along the Quaternary (< 2 ma) faults was more vertical than strike-slip and was responsible for the fragmentation of the Miocene and Pliocene (Neogene) drainage network.

All three hypotheses recognize that thick sediment accumulated in the basins of southwestern Montana during the Paleogene and Neogene (65 – 2 ma), though they offer different details of fill history. This fill, the Bozeman Group, has two formations and is widespread throughout southwestern Montana (Kuenzi and Fields, 1971). The older Renova Formation contains fine-grained volcanic sediment that reflects deposition in low-energy flood plains and ponds of a 200 km-wide basin beginning in the middle Eocene (Paleogene), ca. 42 ma, and continuing into the early Miocene (Neogene), ca. 16 ma (Fritz and Sears, 1993). An angular unconformity representing 1-3 million years separates the Renova Formation from the younger Sixmile Creek Formation. The Sixmile Creek Formation was deposited during the late Miocene and Pliocene, ca. 5 - 16 ma, and includes abundant coarse-grained gravel, reflecting deposition in fast-moving streams (Kuenzi and Fields, 1971). Quaternary sediment and basalt flows unconformably overlie the Sixmile Creek Formation, and the former reflects increasingly localized patterns of deposition as the streams incise the basin fill of the half-grabens. Today, Quaternary sediment forms terraces, and floodplain streams incise and rework older basin deposits (Kuenzi and Fields, 1971).

The multi-staged structural and depositional Cenozoic history of southwestern Montana hypothesized by most researchers (e.g., Rupple, 1993; Fritz and Sears, 1993; Rasmussen, 2003) implies that each modern drainage basin is broadly similar but has locally unique tectonic and depositional histories. The sediment sources of the gravel fill may be from outside the present drainage basin, and flow paths may have changed directions. The large basin(s) that developed during the Eocene was (were) probably later broken into smaller basins with more localized drainage as tectonic uplift continued, either during the Miocene (Neogene) (Rupple, 1993) or the Quaternary (Fritz and Sears, 1993). These structural basins have controlled the modern drainage, and streams now rework sediment from within the drainage basin.

The Nez Perce Basin lies between two major faults and thus forms a small drainage that is part of the larger Jefferson Valley (Fig. 2). Within the basin, several rock types, including gravel, intrusive and extrusive igneous outcrops, and metamorphic bedrock, were noted. The purposes of this project are to identify, characterize, date, and map all Cenozoic and Quaternary gravel units within the basin so that the lithology (rock type), texture, age, and topographic position of each unit can be used to identify the paleotopographic evolution of the area; interpret the tectonic events that have affected the formation of the small Nez Perce basin; and evaluate the formation of the adjacent large Jefferson and Divide basins.

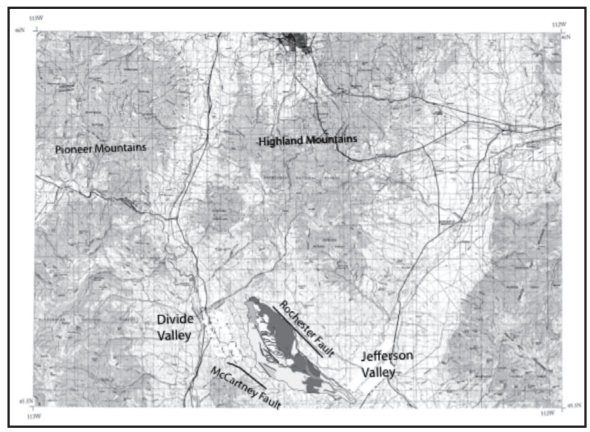

Figure. 2 Regional map of study area and surrounding features.

Methods

Map. Field mapping was done on a 1:24,000 scale, using the 1961 Twin Bridges SW, Wisdom, and Nez Perce 7 ½ minute topographic maps as base maps. All contacts were drawn on the paper maps in the field. A hand-held Garmin global positioning system (GPS) device was used to locate sample locations of the various gravel units and of the igneous rocks for Ar40/Ar39dating. North American Datum 1927 was used on the GPS to coincide with the projection system used on the topographic maps.

In the field, various methods were used to identify, distinguish, and map the metamorphic, volcanic, and gravel units. Metamorphic units were identified using the rock type, such as gneiss or amphibolite, and the dominant mineral, such as garnet. For example, the Archean garnet gneiss was named for its abundance of large garnets. The strike and dip of the foliation were measured at various outcrops in the map area wherever a change in orientation was noted.

Volcanic units were identified on a textural and mineralogical basis. Extrusive volcanic rocks were distinguished from shallow intrusive volcanic rocks by their relatively small crystal size, the presence of air bubbles or vesicles, and the relationship with the adjacent units.

Gravel units were distinguished by their relative grain size and angularity, lithology, and topographic position. The presence of some key lithologic fragments, such as pink quartzite and quartzose sandstone (Proterozoic Belt Group), gneiss and schist (Archean metamorphic rocks), and brown sandstone (Pennsylvanian Quadrant Formation) were noted. Topographic position such as the presence of gravel on the divide or a position within a valley and adjacent to a channel was also used to distinguish the units.

The thickness of each sedimentary deposit was determined using the elevation of the upper and lower contacts on the topographic map. Where a unit was restricted to a small area, the minimum thickness was determined using a Brunton compass to repeatedly measure the eye height of the mappers perpendicular to the bedding through the exposure.

Each unit recognized within the map area was given an informal map name and tentatively correlated with a regional stratigraphic unit. Units included Archean metamorphic gniess, schist, amphibolite, marble, and diabase; Paleogene (Eocene) basaltic and rhyolitic shallow intrusive and extrusive igneous rocks; and Neogene (Miocene) and Quaternary (Pleistocene and Holocene) diamictic and gravel units. All units in the study area are included on the map, but a comprehensive discussion of only the Cenozoic units, including the Paleogene (Eocene) igneous rocks and the Paleogene, Neogene, and Quaternary sand and gravels, is provided in this article.

Digital raster graphs (DRG) of the three maps were used with ArcGIS software to create the digital geologic map. The boundary of the map area, the basin of Nez Perce Creek, was drawn onto the maps in ArcMAP. Standard geologic map symbols and colors were used (Remane, 2002).

Gravel Lithology and Texture. The lithology and texture of the gravels were identified and quantified at 19 locations and included 1 to 10 sites within each tentative map unit. Most (15) of the sample locations were on flat surfaces to reduce the effect of erosion; however, these sites were the most intensely weathered locations, so only the most resistant lithologies were preserved. Four of the 19 sample locations were chosen on either the north- or south-facing slopes of the divide gravel unit in order to evaluate slope processes on the unit. At each location, a 1 m2 area was marked on the ground. The number of cobbles greater than 12.5 cm in diameter at the ground surface was determined as a qualitative measure of the grain size of the deposit and the presence of loess and / or degree of surface erosion. Twenty-five cobbles were removed from the upper few centimeters of the 1 m2 area, and the maximum diameter of the five largest cobbles was measured. Roundness was qualitatively noted in the field.

All 25 cobbles were broken and the lithology recorded. Most lithologies found in the basin were easy to identify, but weathered sandstone, quartzite, and chert cobbles had some similarities and were distinguished based on the following criteria. Sandstones were subdivided based on color: brown, white, or red. Metamorphic quartzite was distinguished from quartz-rich sandstone by a greater degree of cementation, larger apparent grain size, and increased hardness due to recrystallization. Quartzites were subdivided into red, purple, pink, and grey varieties. Chert was identified by the absence of a granular texture.

Ar40/Ar39Dating. Samples of unweathered or very slightly weathered igneous rocks, including basalt, rhyolite, and rhyolitic tuff, were collected for Ar40/Ar39 dating. For basaltic and rhyolitic flows and dikes, multiple samples were collected from each location, and individual samples were labeled. Thin sections of all rock types to be dated were examined to identify the mineralogy and evidence of weathering. Based on examination of thin sections, the eight best samples (least weathered samples and those that included sanidine, biotite, and/or amphibole) were selected for analysis. In some cases, multiple samples from a single location and/or multiple grains from a single sample were analyzed. Four of the selected basalt samples were analyzed using a whole-rock technique. Individual mineral grains (sanidine and biotite) from four additional samples of rhyolitic tuff, granodiorite, and rhyolite were also analyzed.

For the whole-rock analysis, each selected basalt sample was crushed using a jaw crusher and a disc mill and then was hand sieved. The fraction between # 80-100 (180 – 150 microns) was retained, washed, and oven dried. A hand magnet was used to remove large magnetic grains from the dried sample, and the remaining sample was put through a magnetic separator to remove additional small magnetic phenocrysts and inclusions. When the sample looked clean under a low-power microscope, it was rinsed with a 10% hydrochloric acid solution for 10 minutes in an ultrasonic bath, rinsed with deionized water, and oven dried.

For the rhyolite and rhyolitic tuff, single minerals were dated. The rocks were crushed using a jaw crusher and disc mill. These crushed particles were dry sieved to separate the crushed particles into > 500 micron, 250-500 micron, 180-250 micron, and 125-150 micron fractions. Each fraction was examined under a low-power microscope, and the presence of whole and clean biotite, sanidine, and amphibole grains was noted. The fraction with the cleanest grains was washed and oven dried. The biotite, sanidine, and amphibole grains were separated by putting the sample through the magnetic separator to remove most of the magnetic material.

Subsequently, the remaining nonmagnetic particles were put into a heavy liquid to separate the desired minerals. The heavy liquid used to separate biotite had a specific gravity of 3.17 or 2.85 based on the fraction size chosen and was obtained by mixing Bromoform and Methylene Iodide. For sanidine, the heavy liquid mixture had a specific gravity of 2.6. After the desired grains were removed from the sample, they were rinsed with acetone and oven dried. For biotite grains, the sample was shaken over a clean piece of white paper, and the cleanest grains were removed with tweezers. The handpicked biotite grains were put in an ultrasonic bath for 5 minutes to remove dust. The sanidine grains were examined under a low-power microscope, and tweezers were used to pick approximately 100 grains for analysis.

Two machines were used to date the minerals. The individual sanidine grains were run in a MAP 216 mass spectrometer and were heated with a CO2 laser. The basalt whole-rock samples were run on a VG 1200b mass spectrometer, which did not use a CO2 laser. All other minerals were run on both machines, and a resistance furnace instead of a CO2 laser was used to heat the samples.

Results

Geomorphology. The Nez Perce basin is an elongate basin, 17.4 km long and only 5.3 km wide, with a northwest-southeast orientation (Fig. 2, Fig. 7). The western basin margin forms the north-south divide between the Jefferson Valley to the east and the Divide Valley to the west. At the eastern basin margin, Nez Perce Creek is confluent with the Big Hole River in the Jefferson Valley. The northeastern basin margin extends from the northwest to the southeast and parallels the Rochester fault to the north. The southwestern basin margin parallels the McCartney fault to the southwest.

The topography within the basin appears to be more controlled by structure than by stream erosion in the western and central portions of the basin. Here, broad lowlands separate the north-south oriented ridges. In the western portion of the basin, the ridges and lowlands have relatively high relief, and gulleys incise the escarpment between a ridge of Neogene gravels forming the basin divide and the adjacent lowland. Small colluvial fans of locally derived material are present along some of the steep slopes. In the central basin, the ridges and lowlands have relatively low topographic relief. Archean (ca. 3.2 ba) metamorphic rock areas, some of which have a thin veneer of Miocene gravel, underlie the low ridges. Here the Nez Perce channel and its tributaries are incised into the ridges. The intervening lowland is a broad, flat area of Holocene/Quaternary alluvial sediment where the channels are not incised.

In the southwestern section of the New Perce drainage basin, the creek incises the Cenozoic gravel deposits. The incision forms a narrow valley with no floodplain in the upstream portion of this section. Near the confluence of Nez Perce Creek with the Big Hole River, the floodplain becomes wider than upstream and includes two terraces. The oldest terrace is 45 m above the present channel and appears to be a strath terrace (an erosional terrace formed by a stream down-cutting) formed on the Miocene gravel. Inset into the high terrace is a younger depositional terrace 10 to 15 m above a 90-m wide floodplain.

Stratigraphic Units. The following is a discussion of the various units found within the basin, listed from youngest to oldest, based on the field relationships. Each unit is given an informal name and a two- to four-letter abbreviation based upon the unit's age and geomorphic position. Cenozoic units, including four gravel units, basalt and rhyolite flows and intrusions, and a rhyolite tuff, are the focus of this thesis and are discussed in detail. Older Archean units are presented but not discussed.

Holocene channel deposits (Quaternary active channel, Qac) are comprised of well-rounded to angular clasts up to 17 cm in diameter (Appendix A) that are derived from the modern drainage basin. The channel deposit includes quartzite and sandstone clasts, probably from the Proterozoic Belt Supergroup, and gneiss gravel fragments from the local Archean bedrock (Fig. 3). The deposit is found throughout the basin within the active channel (Fig. 7). The gravel has a sand matrix and is interbedded with garnet-bearing coarse sand. The unit has a minimum thickness of 1 meter.

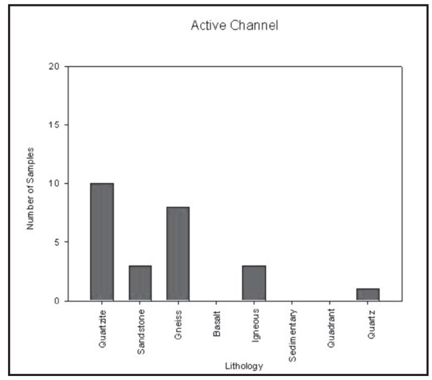

Figure. 3 Graph showing distribution of lithologies found in the active channel.

Holocene alluvium in stream valleys but beyond the present channel (Quaternary floodplain, Qfp) includes well-rounded to angular small clasts up to 5 cm in diameter that are derived from the modern drainage basin. Sand dominates the deposit and includes beds of sand and beds of gravel with a sand matrix (Fig. 4). This deposit is found in the downstream map area, where the valley floor is wide enough to include a floodplain, and in small (a few meters wide) deposits in the northern map area, where the topography is flat adjacent to the active stream channel (Fig. 7). The unit has a minimum thickness of 5 meters, based upon cutbanks of the stream channel.

Holocene/Quaternary alluvium that covers broad valley floors (alluvial sheet deposit, Qad) includes well-rounded to angular clasts up to 2.5 cm in diameter. The gravel fragments include small pebbles of red, pink, and brown quartzites, probably of the Proterozoic Belt Supergroup, well-cemented sandstone clasts, and fragments of local Archean gneiss. This unit forms broad, relatively flat surfaces that are locally adjacent to modern channels in the central portion of the drainage basin and are wider than most of the floodplain in the downstream portion of the basin (Fig. 7). The unit has an unknown thickness but is estimated to be a minimum of 1-5 meters thick based upon cutbanks exposed in the stream channel.

Holocene angular cobbles of rhyolite up to 6 inches in diameter are present on slopes surrounding a rhyolite outcrop (Quaternary colluvium, Qc) in the west-central portion of the drainage basin (Fig. 7). The deposit is of limited extent and is generally less than 5 meters thick.

Miocene well-rounded to sub-angular cobbles generally ≤ 20 cm in diameter form a terrace 45 m above the floodplain along the downstream portion of the Nez Perce Creek (Miocene terrace, Nt) (Fig. 7). The unit includes cobbles of Proterozoic Belt Supergroup quartzite, Archean gneiss, and sandstone. This deposit is similar lithologically to the Miocene divide gravel unit (see below), but the presence of Archean gneiss clasts in this unit and its position forming a terrace of Nez Perce Creek indicate that the deposit and the geomorphic surface are younger than the Miocene divide gravel unit that underlies the uplands. The unit has a minimum

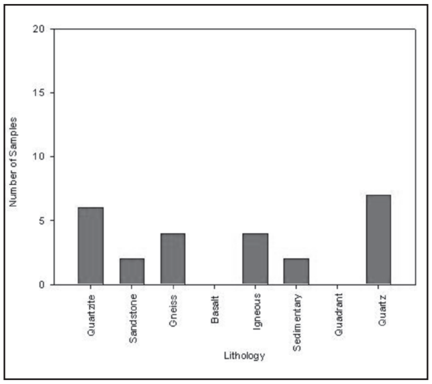

Figure. 4 Graph showing distribution of lithologies found in the floodplain.

thickness of 45 m.

The Miocene divide gravel (Ndg) includes well-rounded clasts up to 45 cm in diameter, with a mean diameter of 22 cm. The clasts are mostly brown, red, pink, and purple quartzite clasts and well-cemented sandstone fragments, probably from the Proterozoic Belt Supergroup. Gneiss clasts from the local Archean metamorphic rocks are absent or are very low in abundance (Fig. 5). This unit forms the western divide of the basin and extends to the east as an upland deposit that caps some ridges in the central part of the basin (Fig. 7). It has a minimum thickness of 170 meters. Gneiss clasts from the local Archean metamorphic rocks are absent or are very low in abundance. The cobbles are up to 30 cm in diameter and have a mean diameter of 20 cm, similar to divide gravels, but a small percentage of the gravel clasts are broken, which increases the mean angularity of the deposit. This subunit was previously mapped as a separate geologic unit with a thickness of 30 m (O'Neill et al., 1996). In the current study, the gravel is included with the divide gravel unit, suggesting a minimum thickness of 170 m, the same as that of the divide gravel.

The lowest gravel deposit exposed in the western portion of the map area is an Eocene debris-flow deposit (Edf) (Fig. 7) that includes subangular to rounded cobbles and boulders up to 4 meters in diameter within a finer matrix. The large clasts include the same lithologies as the younger Miocene gravels (Proterozoic brown, red, pink, and purple quartzite clasts and well-cemented sandstone fragments) and also include clasts of Pennsylvanian Quadrant sandstone and Eocene basalt, which are not found in any other gravel unit (Fig. 6). The thickness of this unit is approximately 40 meters.

Eocene basalt (Eb) flows are found along the western border of the drainage basin, interlayered with the debris flow deposit (Fig. 7). These extrusive basalt flows are very weathered and include phenocrysts of biotite. The minimum thickness is estimated to be 10 m, based upon the outcrop height on slopes.

A gray Eocene rhyolitic tuff (Et) weathers pink and has rounded quartzite and limestone fragments and angular gneiss and pumice fragments up to 5 cm in diameter in a fine-grained matrix. It underlies the Miocene debris flow and overlies the Archaen gneiss. The tuff is at least 13.5 m thick but is found in only one isolated location along a gulley in the northwestern portion of the drainage basin (Fig. 7).

The Eocene rhyolite (Er) has a purplish-gray to pinkish-gray matrix with phenocrysts (included minerals) of hornblende, sanidine, quartz, plagioclase, and biotite. It also displays distinctive chalcedony-filled cavities. The rhyolite outcrop occurs on the east-central border of the drainage basin and intrudes into Archean gneiss (Fig. 7). Previous K-Ar dates on the rhyolite, between 47 and 51 ma (Hanneman and Wideman, 1991), are consistent but not as precise as the Ar40-Ar39 dates reported in the current study (Table 1, Appendix B). The minimum thickness of this unit is estimated to be 25 m based upon outcrop elevation above the surrounding topography.

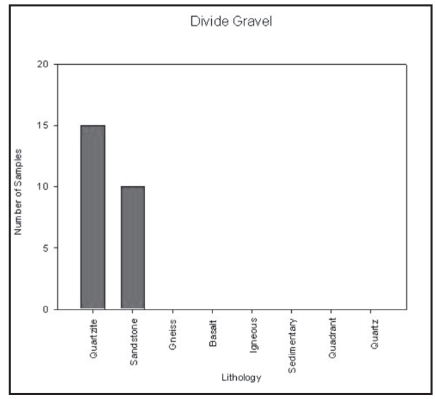

Figure. 5 Graph showing distribution of lithologies from the divide gravel unit.

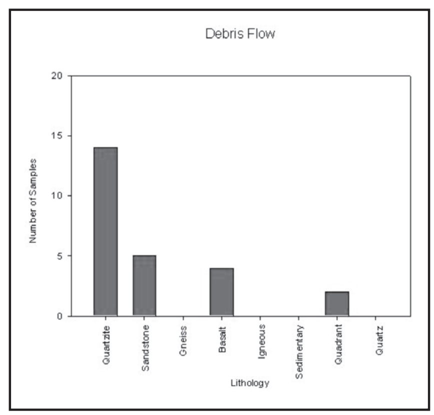

Figure. 6 Graph showing distribution of lithologies from the debris flow unit.

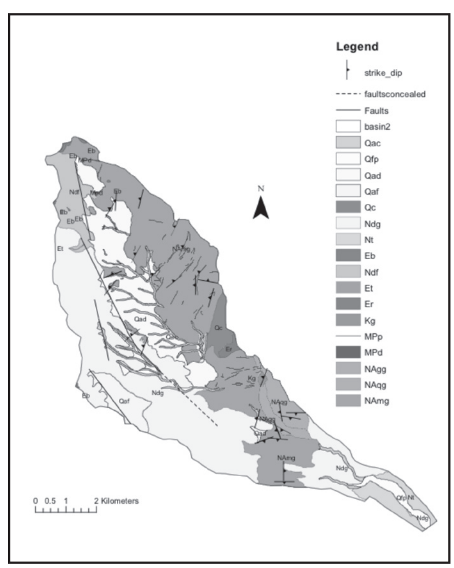

Figure. 7 Geologic map displaying all units. Faults represented by black lines.

Structure. Faults within and adjacent to the Nez Perce basin are the dominant control of the present landscape. The mapped faults in the study area are all within the gravel units of the western side of the drainage basin divide, except for one large fault that trends north-south in the middle of the basin and separates the Miocene gravel units from Archean gneiss.

The faults within the gravel units were initially identified on satellite imagery (Google Earth images), in aerial photographs, and in the field as north to north-northeast lineaments that separate blocks of different elevations. Mapping confirmed that the gravel unit that forms the surface of the blocks is the same lithologic unit, the Miocene divide gravel, though at a different elevation. The block margins are linear, and the block surfaces are relatively flat but do not necessarily slope down toward the basin. Streams do not drain all of the lower-elevation blocks, indicating that these low topographic features are not due to fluvial erosion. One of the blocks does have minor drainage that crosses it, but the drainages are very small ephemeral stream channels and are out of scale compared to the width of the block, which is close to 300 m.

Movement along the faults was generally normal (vertical). A vertical offset of up to 30 m is estimated using the relief between adjacent blocks. The down-faulted blocks have a veneer of late Quaternary gravels that is missing on the high topographic blocks, indicating that the faulting predates the late Quaternary. The offset of the Miocene divide gravel indicates that faulting postdates the middle Miocene. An alluvial fan at the base of the divide gravel in the southwestern map area shows no evidence of faulting within the fan but has accumulated on the downthrown side of a normal fault and post-dates the faulting, probably forming as a result of increased topographic relief.

Ages of Volcanic Rocks. Four igneous units in or adjacent to the map area that include basaltic and rhyolitic volcanic flows, rhyolitic pyroclastic debris, and basaltic intrusions have Ar 40/Ar 39 dates of ages that overlap and range between 47.5 to 49.9 ma (Table 1). This mapping and dating indicate that volcanic activity was widespread, though perhaps not volumetrically important, within this small geographic area during this relatively brief interval. A rhyolite flow is dated 47.9 ± 0.6 to 49.25 ± 0.29 ma, which overlaps the age of the rhyolite tuff, dated 48.5 ± 0.2 to 48.84 ± 0.17 ma, suggesting that the lava flow and the pyroclastic eruption are related in time and space. Basalt intrusions and flows have dates ranging from 47.5 to 49.7 that are statistically the same as those of the rhyolitic eruptions.

The dated volcanic debris in association with the debris flow unit allows the age of that debris flow unit to be closely bracketed because dated units underlie and intrude the debris flow. Six dates on single grains (sandidine and biotite) from the rhyolitic tuff underneath the debris flow range from 48.5 ± 0.2 to 48.84 ± 0.17 ma and provide a maximum age of 49.01 ma for the debris flow. Unfortunately, a basalt flow interbedded with the debris flow was too weathered to date. Three whole-rock dates on basalt dikes that crosscut the debris flow range from 48.9 to 47.5 ma and provide a minimum age for the debris flow, indicating that the debris flow is older than 47.5 ma (see Table 1, Appendix B). An additional whole-rock basalt date on a flow beneath the divide gravel, but with no known relationship to the debris-flow unit which is missing at this location, is 49.2 to 49.7 ma. The similarity of the date from this flow to that of the nearby intrusions indicates that both volcanic events are probably related. The dating results are displayed in more detail in Appendix B.

Sample #	Rock Type	Low Age (Mill. Yrs.)	High Age (Mill.Yrs.)
1	Basalt *	47.5	48.5 ± 0.1
2	Rhyolitic Tuff	48.59 ± 0.04	48.6 ± 0.12
3	Basalt *	48.7	48.7
4	Rhyolitic Tuff *	48.5 ± 0.2	48.84 ± 0.17
5	Basalt*	48.5	48.9
6	Rhyolite	47.9 ± 0.6	49.25 ± 0.29
7	Basalt	49.2	49.7
8	Granodiorite	80.5	80.5

Table 1. Results of the Ar 40/Ar 39 dating showing minimum and maximum ages and uncertainties. Asterisks denote samples used to bracket the debris flow.

Discussion

Gravel deposits are extensive in the western and eastern portions of the drainage basin and form a variety of geomorphic surfaces. Subdivision of the gravels based on the surfaces is difficult without some quantification of lithology and texture because faulting rather than stream erosion and incision may account for these surfaces. O'Neill et al. (1996) subdivided the upland gravels in the western portion of the basin into three units, listed in stratigraphic order: a Paleogene debris flow, a Neogene sedimentary gravel unit, and a Neogene fluvial gravel. The lowest unit, the Paleogene debris flow, forms the basin divide at the northwest margin of the basin and stratigraphically underlies the upper Neogene sedimentary gravel to the south along the rest of the western divide. The lower Neogene fluvial gravel underlies the secondary divide surfaces, but nowhere is there a clear stratigraphic relationship of this gravel with either an older debris flow or a younger Neogene fluvial gravel in the field, nor is there a clear lithologic difference between the two Neogene units. Based on geomorphology, O'Neill et al. (1996) recognized that the Neogene fluvial gravel was not a terrace deposit formed by incision. Rather, the stratigraphic position of the Neogene fluvial gravel is based on a lower topographic position of the Neogene sedimentary gravel than the Neogene fluvial gravel, and the Neogene sedimentary gravel is assumed to underlie the youngest Neogene fluvial gravel.

The results of the study indicate that the Neogene fluvial gravel is not a product of incision and thus is not younger than the Neogene sedimentary gravel. This conclusion is based on the fact that it is not inset within valleys, there are no stream channels in some of the topographically low areas mapped as Neogene fluvial gravel, and the surfaces slope at various angles and in different directions.

Though the lower gravels (Neogene sedimentary gravel) (O'Neill et al, 1996) are downslope from the divide gravel (Neogene fluvial gravel) (O'Neill et al, 1996), they have nearly identical lithologies and similar grain sizes, suggesting that they have a similar source (Fig. 2). The lithology of these units includes

Proterozoic quartzites and sandstones, probably from the Belt Supergroup, which is exposed in the Highland Mountains to the north. Archean gneiss is absent from both units, as is Quadrant Sandstone. Statistical analysis of the textural data using a One-Way Repeated Measures of Variance (ANOVA) test was used to compare the four major gravel units of this study. This test found a significant difference in grain size between each gravel unit, except those of the divide gravel and the lower gravel units, which are statistically the same (Fig. 8). If the older gravel had been reworked, the resulting lower gravel most likely would have resulted in a smaller grain size.

The results of the current study do not concur with those of O'Neill et al. (1996), who reported that the lower gravel (Neogene sedimentary gravel) was older than the divide gravel (Neogene fluvial gravel). When the lower basin gravel was exposed, either the divide gravel was not deposited and did not bury the lower basin gravel in these locations or it was subsequently stripped from these locations. Stripping of the upper Neogene gravel would require fluvial action, but no streams are present on this surface. It is also unlikely that two thick (between 150 and 300 m) tongues of divide gravel with steep slopes were deposited over the lower basin gravel.

The results of the current study indicate that the lower basin gravel and the divide gravel are parts of one unit separated by faults with some component of dip-slip movement. Lineament-bounded blocks of different elevations are slightly tilted at various angles to the south, and minor stream channels are offset where they cross the lineaments. The resulting topography is a series of small horsts and grabens that generally become lower in elevation to the east. The similar gravel lithology and texture associated with each surface support a faulting hypothesis. It is possible that the broken clasts could have been ruptured during faulting because more broken clasts were found downslope than upslope from the proposed faults. Faulting with either dip-slip motion (Reynolds, 1979) or oblique strike-slip motion (Rupple, 1993; Fritz and Sears, 1993) is abundant in the northern Basin and Range of southwestern Montana and likely occurs in the study area also.

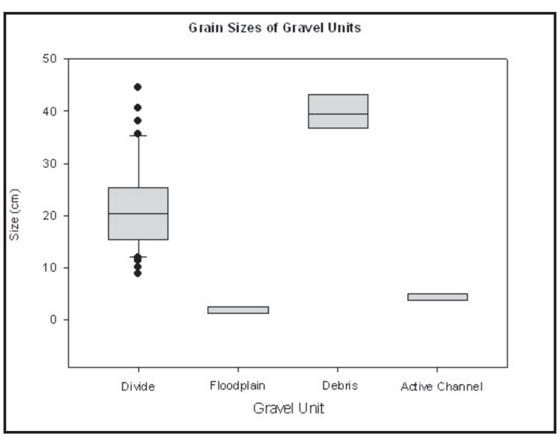

Figure 8. A comparison of the grain sizes of the four main gravel units.

Surface Erosion. The number of cobbles > 12.6 cm exposed on the ground surface was greater in the divide gravel than in the lower gravel unit, but analysis by a t-test showed no statistical significance. The exposure of more clasts in the divide gravel may simply be a result of wind and gravity erosion removing more fine-grained material on uplifted blocks than on down-dropped blocks, protected areas where fines may be preserved and even accumulate. A study was also performed within the basin of cobbles exposed on two northern and two southern facing slopes of the divide gravel unit. A greater number of cobbles was found exposed on the south slopes (average of 6.5 vs. average of 2), though this number was not shown to be statistically significant by a t-test. This finding may also be a result of wind erosion moving fine-grained material off the north-facing slopes at a more rapid rate than that off the south-facing slopes.

Source of the Gravels. The Alluvial Sheet Deposit was determined to be the youngest of the four major units. Its relatively small grain size (mean of 1.8 cm) and the presence of all lithologies found within the basin, including gneiss, quartzite, sandstone, basalt, and quartz, suggest that the Alluvial Sheet was deposited after the present basin was formed and the gneiss was exposed. Its source is entirely within the present basin.

Though there is some debate as to the physical relationship between the divide gravel and the lower gravel units, lithologic evidence suggests that they have a similar source. The presence of well-cemented arkose and red, pink, and purple quartzite implies that both units are derived in part from the erosion of the Belt Supergroup, which includes these lithologies (Kuenzi and Fields, 1971; Janecke et al., 2000). The Belt Supergroup is present to the northwest in the Pioneer Mountains and to the north in the Highland Mountains (Fig. 3). The Quadrant Formation is absent in the divide and lower gravel units and is exposed in the Pioneer Mountains but not on the south side of the Highland Mountains. Based on the absence of the Quadrant Formation, the probable source is the southern Highland Mountains to the north (Fig. 3).

The debris flow unit was determined to have a different source than the three younger gravel units. Quadrant Sandstone is present only in this unit, and there is no exposure of the Quadrant Formation on the southern side of the Highland Mountains to the north or the northern side of McCartney Mountain to the south; rather, the unit is exposed in the Pioneer Mountains and the Divide basin to the west (Fig. 3). The flow also includes some clasts of the local Archean gneiss, which underlies the debris flow and may have been incorporated within the deposit, suggesting that the debris flow was deposited at a different time than any of the other gravel units that do not include gneiss fragments.

Conclusions

The relationships among the four main gravel units in the Nez Perce Basin can be interpreted in several ways, each reflecting a different focus on topography, lithology, and/or grain size. The preferred interpretation for the current article focuses on the structural controls and concludes that the topography of the Nez Perce Basin is dominantly a reflection of Cenozoic structural and tectonic events rather than Quaternary fluvial processes. The lithology and grain sizes support the conclusion that faulting offsets the older two gravel units and controls the distribution of the younger gravel units.

From youngest to oldest, the four main gravel units in the study area are the Holocene channel deposit, the Quaternary floodplain deposit, the Miocene divide gravel, and the Miocene debris flow. The source of the channel and floodplain deposits is within the present basin and postdates the structural development of the basin, as determined by the presence of lithologies derived solely from within the present basin and a relatively small grain size (from 1 to 17 cm). In contrast, the source of the divide gravel is the Highland Mountains to the north, based upon the presence of well-rounded red and pink quartzites from the Belt Supergroup, which outcrops in the Highland Mountains. The source of the debris flow is the Pioneer Mountains to the west, based upon the presence of Pennsylvanian Quadrant sandstone, which outcrops in the Pioneer Mountains (Fig. 3). An additional gravel unit, informally termed the lower gravel, has been included in the divide gravel unit in this study, based on a statistically similar lithology and texture. This report concludes that small-scale normal faulting offset a single unit and created the elevation differences found within this unit. The changing lithologies, textures, and geomorphic positions of the gravels suggest substantial changes in streamflow patterns within the region, first between the Eocene and Miocene and subsequently between the Miocene and the Quaternary.

The Ar40/Ar 39 date of ca. 48 ma on basalt and rhyolitic tuff that underlie, are interbedded, and crosscut the debris flow unit indicates that the debris flow is middle Eocene. No igneous materials are associated with the youngest three gravel units, and Ar40/Ar 39 dating was not useful in providing more exact ages for the units.

Though the results of this study are limited to a small area, they give some insight into the structural history of that area. The presence of normal faulting within a single unit that has been determined to be of Miocene age suggests that extension was occurring at least 15 million years ago. This initial conclusion supports all three hypotheses proposed by Reynolds (1979), Rupple (1993), and Fritz and Sears (1993), who claim that the present-day basins and ranges were formed due to extensional events. However, the divide gravel unit was determined to correlate with the regional Sixmile Creek Formation, which is late Miocene to early Pliocene (ca. 5-16 ma). If this correlation is correct, data from this study best support the hypothesis of Fritz and Sears (1993), which claims that modern basin development began more recently than the middle Miocene. Without the faulting in younger units and a more regional examination, however, it is impossible to support one hypothesis over the others.

Acknowledgements

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Mentor comments: Professor Margaret Guccione speaks highly of Rose Feinstein's initiative in completing this research project. The Teaching Academy review committee readily recognized the scope and excellence of this work by awarding it one of the 2010 Undergraduate Research Awards.

*Rose A. Feinstein, a proactive and very capable student, received funding for her project, **Geologic Map of the Nez Perce Drainage***

***Basin**, Southwestern Montana, from the EDMAP program of the US Geological Survey (USGS). The EDMAP program is to provide money to students for mapping projects that will teach them mapping skills. Funding is very competitive and was fully funded, though only about 60% of the proposals are funded and only about 15% of the proposals are fully funded. It was quite an accomplishment! Not only did Rose produce the map, the only requirement for the grant, but she wrote a manuscript that described and interpreted the sedimentology, lithology, and structure of the units that are present in the map area and contributed a better understanding of the structural development of the mountains and valleys of southwestern Montana. Her project was strongly supported by the Montana Bureau of Mines and Geology and several of Bureau geologists visited her in the field to see her research. In addition, a U.S. Geological Survey scientist, intrigued with the project, volunteered to fly to Montana at no expense to the grant to help Rose sample the igneous rocks and offered the use of his lab in Reston, Virginia for Rose to prepare the samples for analysis, and analyzed the samples. This was a fantastic experience for Rose and the resulting dates are of interest to, have been requested by, and have been shared with the USGS and the Montana Bureau of Mines and Geology. The support, both financial and scientific, of the USGS and the Montana Bureau of Mines and Geology to this project done by an undergraduate, has been tremendous and demonstrates that the project has significant scientific value, far better than any mentor can extol.Rose's project has contributed to science in several ways. First she generated a number of dates on volcanic materials using a state-of-the-art dating technique in a state-of-the-art lab from an area where no dates of this caliber were available, she recognized structural elements that had not been recognized in prior mapping by using the gravel lithology, and she has applied this information to a more complete understanding of the development of the southern Highland Mountains and adjacent Jefferson and divide valley.*

Appendix A. General data collected from gravel units.

Unit	Location	Surface > 12.7 cm	5 Largest	Qtzite	SS	Basalt	Gneiss	Quad	Ig	Sed	Qtz
Ndg	N 45.33.514 W 112.33.607	9	19.05 24.765 22.86 16.51 15.875	18	4	1	0	0	0	2	0
Qaf	N 45.34.924 W 112.33.968	3	21.59 12.065 22.225 11.43 17.145	15	10	0	0	0	0	0	0
Ndg	N 45.34.015 W 112.33.197	3	25.4 15.24 20.32 13.97 30.48	16	9	0	0	0	0	0	0
Ndg	N 45.35.843 W 112.34.151	6	40.64 35.56 44.45 27.94 38.1	15	10	0	0	0	0	0	0
Ndg	N 45.32.924 W 112.31.501	3	25.4 22.86 27.94 19.05 21.59	10	14	1	0	0	0	0	0
Ndg	N 45.34.059 W 112.33.196	7	33.02 19.05 21.59 15.87 22.86	16	9	0	0	0	0	0	0
Ndg	N 45.35.467 W 112.34.225	6	30.48 17.78 24.13 17.78 17.78	13	12	0	0	0	0	0	0
Ndg	N 45.35.391 W 112.34.151	1	38.1 17.78 25.4 16.51 20.32	12	13	0	0	0	0	0	0
Mdf	N 45.36.479 W 112.34.129	11	40.64 39.37 45.72 35.56 38.1	14	5	4	0	2	0	0	0
Qaf	N 45.32.966 W 112.31.930	0	5.08 4.445 5.715 4.445 5.08								
Ndg	N 45.34.718 W 112.32.085	5	30.48 24.5 22.86 24.13 22.86	9	14	2	0	0	0	0	0
Qac	N 45.31.863 W 112.25.860	0	3.81 5.08 3.81 5.08 3.81	8	5	0	9	0	0	1	1
Ndg	N 45.31.353 W 112.25.209	4	27.94 15.24 33.02 16.51 25.24	12	13	0	0	0	0	0	0
Nt	N 45.31.214 W 112.25.080	0	2.54 5.08 3.81 2.54 3.81	9	12	0	1	0	0	1	2
Nt	N 45.34.067 W 112.31.717	2	38.1 14.605 15.24 17.78 13.97	15	10	0	0	0	0	0	0
Qfp	N 45.36.365 W 112.32.423	0	2.54 3.81 3.81 2.54 3.81	6	2	0	4	0	4	2	7
Qac	N 45.33.094 W 112.28.964	2	10.16 10.16 12.7 10.16 17.78	10	3	0	8	0	3	0	1
Ndg	N 45.32.814 W 112.29.216	2	12.7 11.43 10.16 8.89 12.7	11	11	1	1	0	0	1	0

Appendix B. Results of Argon dating.

	Sample #	Locationt NAD 27	Stratigraphic unit/position	Rock type	material dated	Dating method	Age	Uncertainty, 1 sigma	msd	Stage
1	071709-03	45° 33.651'N	Granodiorite intrusion - Boulder Batholith	granodiorite	biotite	single grain, total fusion	80.5	NA	large	late Cretaceous
		112° 28.941'W								
2	071709-04c	45° 33.479'N	Basalt flows that underlie divide gravel (Sixmile Creek Fm) south divide - Lowland Creek Field (Challis Fm)	Basalt	whole rock		49.2	NA		middle Eocene
2	071709-04e	112° 33.734'W		Basalt	whole rock		49.7	NA		middle Eocene
3	071709-02	45.34.311N	Rhyolite flow from volcanic "neck" - Lowland Creek Field (Challis Fm)	rhyolite	biotite, machine 1	single grain, total fusion	49.25	± 0.29		middle Eocene
3	071709-02	112.29.720W	Rhyolite flow from volcanic "neck" - Lowland Creek Field (Challis Fm)	rhyolite	biotite, machine 2	single grain, total fusion	49.01	± 0.3		middle Eocene
3	071709-02		Rhyolite flow from volcanic "neck" - Lowland Creek Field (Challis Fm)	rhyolite	biotite	single grain, total fusion	47.9	± 0.6		middle Eocene
4	071609-03a	45° 36.668'N	Basaltic dikes that intrude debris flow (preRenova Fm), north divide - Lowland Creek Field (Challis Fm)	Basalt	whole rock		48.9	NA		middle Eocene
4	071609-03b	112° 34.268'W		Basalt	whole rock		48.5	NA		middle Eocene
5	071609-05	45° 36.074'N	below debris flow (preRenova Fm) , bottom of tuff - Lowland Creek Field (Challis Fm)	tuff	sanidine	single grain, total fusion	48.6	± 0.2		middle Eocene
5	071609-05	112° 33.468'W	below debris flow (preRenova Fm) , bottom of tuff - Lowland Creek Field (Challis Fm)	tuff	sanidine	single grain, total fusion	48.5	± 0.2		middle Eocene
5	071609-05		below debris flow (preRenova Fm) , bottom of tuff - Lowland Creek Field (Challis Fm)	tuff	biotite, machine 1	single grain, total fusion	48.66	± 0.2		middle Eocene
5	071609-05		below debris flow (preRenova Fm) , bottom of tuff - Lowland Creek Field (Challis Fm)	tuff	biotite, machine 2	single grain, total fusion	48.84	± 0.17		middle Eocene
6	071609-02b	45° 36.849'N	Basaltic dikes that intrude debris flow (preRenova Fm), north divide - Lowland Creek Field (Challis Fm)	Basalt	whole rock		48.7	NA		middle Eocene
6	071609-02c	112° 34.284'W		Basalt	whole rock		48.7	NA		middle Eocene
7	071609-01	45° 36.001'N	below debris flow (preRenova Fm) , top of tuff - Lowland Creek Field (Challils Fm)	tuff	sanidine, small grain	single grain, total fusion	48.59	± 0.04		middle Eocene
7	071609-01	112° 33.753'W	below debris flow (preRenova Fm) , top of tuff - Lowland Creek Field (Challis Fm)	tuff	sanidine, large grain	single grain, total fusion	48.6	± 0.12	1.98	middle Eocene
8	071609-04e	45° 36.498'N	Basaltic dikes that intrude debris flow (preRenova Fm), north divide - Lowland Creek Field (Challis Fm)	Basalt	whole rock		47.5	NA		middle Eocene
8	071609-04a	112° 34.322'W		Basalt	whole rock		48.5	± 0.1	1	middle Eocene